Potential of a linear collider for lepton flavour violation studies in the susy seesaw

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Abstract. We study the potential of an $e^{\pm}e^{-}$ Linear Collider for charged lepton flavour violation studies in a supersymmetric framework where neutrino masses and mixings are explained by a type-I seesaw. Focusing on e-μ flavour transitions, we evaluate the background from standard model and supersymmetric charged currents to the $e\mu + \not{E}_T$ signal. We study the energy dependence of both signal and background, and the effect of beam polarisation in increasing the signal over background significance. Finally, we consider the $\mu^- \mu^- + \not{E}_T$ final state in $e^- e^-$ collisions that, despite being signal suppressed by requiring two e-μ flavour transitions, is found to be a clear signature of charged lepton flavour violation due to a very reduced standard model background. This contribution summarises part of the work done in [1].

1. Introduction

A high-energy lepton collider (LC) [2] offers the possibility of direct production of lepton number (L) carrying heavy states (such as sleptons $\tilde{l}$ in supersymmetry) and of doing precision physics profiting from low QCD activity. The possibility of polarising the colliding beams with great accuracy makes the physics potential of a lepton collider even more ambitious. Indeed, by polarising the initial beams, one is able to (approximately) project the chirality of the couplings intervening in the primary production process, thus probing the chirality structure of an underlying new physics model. Polarisation can also be used to suppress the background from Standard Model (SM) processes (e.g. from weak charged currents) to charged lepton flavour violation (cLFV) signals. Moreover, threshold scans of chirality projected primary produced particles can be used to determine their masses [3].

Supersymmetry (SUSY) remains one of the most attractive extensions of the SM. Thus, a very appealing mechanism to explain the smallness of neutrino masses and generate neutrino mixing is to consider a supersymmetric seesaw. A type-I seesaw mechanism in which the right-handed (RH) neutrinos have masses close to the grand unification (GUT) scale, generates neutrino masses and mixings with naturally large Yukawa couplings, and can offer an explanation for the observed baryon asymmetry of the universe. However, the drawback of such a set-up is that it

is very hard to probe since the very heavy RH neutrinos cannot be produced at colliders. On the other hand, in a supersymmetric type-I seesaw (usually dubbed SUSY seesaw) the radiative corrections generate flavour violation in the slepton sector [4], giving additional sources of LFV at low energy. At a high-energy LC, sleptons can be copiously produced and their decays lead to potentially observable cLFV final states, thus providing a unique probe of this mass generation mechanism.

SUSY-seesaw induced cLFV at a LC has been studied in [5, 6] focusing on τ-μ flavour violation, while in [7] slepton driven cLFV was also considered but without relying on a particular origin of slepton mixing.

Motivated by the excellent muon reconstruction capabilities and the recently improved upper-limit on $\mu \to e\gamma$ [8], we studied the SUSY seesaw induced μ-e cLFV and its discovery potential at a LC working with polarisable beams [1].

2. The SUSY seesaw

The SUSY seesaw model comprises the minimal supersymmetric standard model (MSSM) extended by three[1] chiral superfields $\hat{N}_i^c \sim \left(\nu^c, \tilde{\nu}_R^\dagger\right)_i$, so-called RH neutrino superfields, that are singlets under the SM gauge group. The leptonic part of the superpotential is given by

$$\mathcal{W}^{\text{lepton}} = \frac{1}{2}\hat{N}^c M_N \hat{N}^c + \hat{N}^c Y^\nu \hat{L}\hat{H}_2 + \hat{E}^c Y^l \hat{L}\hat{H}_1 \,. \tag{1}$$

Hereafter we work in a flavour basis where the charged lepton Yukawa couplings Y^l and the RH neutrino mass matrix M_N are diagonal. The slepton soft breaking terms are

$$\begin{aligned}\mathcal{V}^{\text{slepton}}_{\text{soft}} \;=\; & m_{\tilde{L}}^2 \tilde{\ell}_L \tilde{\ell}_L^* + m_{\tilde{E}}^2 \tilde{\ell}_R \tilde{\ell}_R^* + m_{\tilde{\nu}_R}^2 \tilde{\nu}_R \tilde{\nu}_R^* \\ & + \left(A_l H_1 \tilde{l}_L \tilde{l}_R^* + A_\nu H_2 \tilde{\nu}_L \tilde{\nu}_R^* + B_\nu \tilde{\nu}_R \tilde{\nu}_R + \text{H.c.}\right) \,.\end{aligned} \tag{2}$$

Our analysis is conducted in a framework where SUSY breaking is flavour blind (as in minimal supergravity mediated SUSY breaking) and the soft breaking parameters satisfy certain universality conditions at a high-energy scale, which we take to be the gauge coupling unification scale $M_{\text{GUT}} \sim 10^{16}$ GeV:

$$\left(m_{\tilde{L}}\right)_{ij}^2 = \left(m_{\tilde{E}}\right)_{ij}^2 = (m_{\tilde{\nu}_R})_{ij}^2 = m_0^2 \delta_{ij} \,, \tag{3}$$

$$(A_l)_{ij} = A_0 \left(Y^l\right)_{ij} \,, (A_\nu)_{ij} = A_0 \left(Y^\nu\right)_{ij} \,, \tag{4}$$

where m_0 and A_0 are the universal scalar soft-breaking mass and trilinear couplings of the constrained MSSM (cMSSM), and i, j denote lepton flavour indices ($i, j = 1, 2, 3$).

After electroweak (EW) symmetry breaking, the neutrino mass matrix is approximately given by $m_\nu \simeq -m_D^{\nu}{}^T M_N^{-1} m_D^\nu$, where $m_D^\nu = Y^\nu v_2$ and v_i is the vacuum expectation value of H_i ($v_{1(2)} = v \cos(\sin)\beta$, with $v = 174$ GeV). A convenient means of parametrizing the neutrino Yukawa couplings, while at the same time allowing to accommodate the experimental data, is given by the Casas-Ibarra parametrization [9], which reads at the seesaw scale M_N

$$Y^\nu v_2 = m_D^\nu = i\sqrt{M_N^{\text{diag}}}R\sqrt{m_\nu^{\text{diag}}}U_{\text{MNS}}^\dagger \,, \tag{5}$$

where U_{MNS} is the light neutrino mixing matrix and R is a 3×3 complex orthogonal matrix that encodes the possible mixings involving RH neutrinos. We use the standard parametrization for the U_{MNS}, with the three mixing angles in the intervals favoured by current data [10].

[1] We assume that the number of RH neutrino generations mimics the number of generations of SM fermions. In fact, two are sufficient in order to comply with neutrino oscillation parameters.

2.1. Flavour violation in the slepton sector

Due to the non-trivial flavour structure of Y^ν, the running from M_{GUT} down to the seesaw scale will induce flavour mixing [4] in the otherwise approximately flavour conserving slepton soft breaking terms. This running is more pronounced in the soft breaking terms involving slepton doublets since these have local interactions with the RH (s)neutrinos. At leading order, the flavour mixing induced by these radiative corrections has the form

$$\left(\Delta m_{\tilde{L}}^2\right)_{ij} = -\frac{1}{8\pi^2}\left(3m_0^2 + A_0^2\right)\left(Y^{\nu\dagger}LY^\nu\right)_{ij},\tag{6}$$

$$(\Delta A_l)_{ij} = -\frac{3}{16\pi^2}A_0 Y_{ij}^l\left(Y^{\nu\dagger}LY^\nu\right)_{ij}\; ;\; L_{kl} \equiv \log\left(\frac{M_{\mathrm{GUT}}}{M_{N_k}}\right)\delta_{kl}.\tag{7}$$

The amount of flavour violation in the slepton sector is encoded in $\left(Y^{\nu\dagger}LY^\nu\right)_{ij}$ which, as made explicit by equation (5), is related to high- and low-energy neutrino parameters.

3. cLFV in $e^\pm e^-$ collisions

At collider energies, i.e. at energies of the order of the TeV, the (high-scale) SUSY seesaw with the aforementioned assumptions for SUSY breaking can be interpreted as a minimal deviation from the cMSSM that allows for flavour mixing in the slepton soft breaking parameters, since processes mediated by RH (s)neutrinos are greatly suppressed due to the very high seesaw scale. We stress that, contrary to other analysis, the origin of this flavour mixing is rooted on, albeit not singly determined by, neutrino oscillations.

In the SUSY seesaw model, as in the MSSM, the sparticle production in e^+e^- collisions are dominated by the following 2-body processes

$$e^+e^- \to \tilde{\ell}_i^+\tilde{\ell}_j^-\;,\; \chi_A^0\chi_B^0,\; \chi_A^+\chi_B^-,\; \tilde{\nu}_i^*\tilde{\nu}_j.\tag{8}$$

For e^-e^- collisions, the available channels are considerably restricted, and we have

$$e^-e^- \to \tilde{\ell}_i^-\tilde{\ell}_j^-.\tag{9}$$

Since SUSY-seesaw induced cLFV final states are dominated by slepton decays via slepton-lepton-(EW gaugino) interactions, it is useful to distinguish two cases with respect to the slepton/EW gaugino mass hierarchy. A dark-matter motivated scenario in which sleptons are heavier than the EW gauginos occurs in the so-called "Higgs funnel" region, while the opposite hierarchy happens in the so-called co-annihilation region. We thus define two types of points to guide the subsequent analysis

- F points: $m_{\tilde{\ell},\tilde{\nu}} > m_{\chi_2^0,\chi_1^+}$ and $m_{\chi_2^0,\chi_1^+} > m_{\tilde{\tau}_1}$;
- C points: $m_{\tilde{\ell},\tilde{\nu}} < m_{\chi_2^0,\chi_1^+}$ and $m_{\chi_1^0} \lesssim m_{\tilde{\tau}_1}$.

In table 1 we give two C- and one F-type points that will be used in the numerical analysis.

In the model under consideration, R-parity is conserved implying that the final states we are interested in, i.e. those with intervening sleptons, have an even number of χ_1^0 (the lightest supersymmetric particle, the LSP) which escape the detector without interacting. Hence, we focus our attention on cLFV in processes with di-lepton final states plus missing transverse momenta, $\not{E}_T$. The main source of background arises from weak charged currents producing neutrinos which, analogously to the LSP, escape undetected. These are of two types: the SM charged current backgrounds (type B) in which all $\not{E}_T$ is due to neutrinos; SUSY charged

Table 1. Representative points used in the numerical analysis.

	C_1	C_2	F
m_0 (GeV)	150	200	750
$M_{1/2}$ (GeV)	727.9	949.2	872.1
$\tan\beta$	10	10	52
A_0 (GeV)	0	0	0
$\text{sign}(\mu)$	1	1	1

current backgrounds (type C) in which $\not{E}_T$ contains both neutrinos and LSPs. Here, we study the following possibilities:

$$e^\pm e^- \to \begin{cases} e^\pm\mu^- + 2\chi_1^0 & \text{(A)} \\ e^\pm\mu^- + 2\chi_1^0 + (2,4)\nu & \text{(B)} \\ e^\pm\mu^- + (2,4)\nu & \text{(C)} \end{cases} \qquad (10)$$

where (A) is the signal. In table 2 we classify the main sources of (B) and (C) backgrounds in e^+e^- collisions, in which we allow for leptonically decaying τs, Ws and Zs. Backgrounds in e^-e^- collisions can be similarly classified. However, $e^-e^- \to W^-W^-$ is very small, being suppressed by powers of m_ν/M_W, and $e^-e^- \to \tau^-\tau^-$ vanishes.

Table 2. SUSY charged current backgrounds (B) and SM charged current backgrounds (C), with the corresponding total cross section (order of magnitude) for unpolarised beams, for the signal $e^+\mu^- + 2\chi_1^0$.

SUSY bckg (type B) $\lesssim 5$ fb	0τ	$e^+\mu^- + (\bar\nu\nu, 2\bar\nu\nu) + 2\chi_1^0$
	$\tau+0\nu$	$(e^+\tau^-, \tau^+\mu^-, \tau^+\tau^-) + 2\chi_1^0$
	$\tau+2\nu$	$(e^+\tau^-, \tau^+\mu^-) + \bar\nu\nu + 2\chi_1^0$
SM bckg (type C) $\approx 10^2$ fb	W-strahlung	$W^-(e^+,\tau^+)\nu,\ W^+(\mu^-,\tau^-)\bar\nu$
	W-pair	W^+W^-
	τ-pair	$\tau^+\tau^-$

SM charged current backgrounds could *in principle* be reduced by devising kinematical cuts that rely on the fact that neutrinos are much lighter than the LSP and that the seeding processes have different topologies. However, that analysis is beyond the scope of our work. In our work [1] we conduct a phenomenological analysis, focusing on theoretical estimations of the expected number of events at a LC operating at a given centre of mass energy with the possibility of polarised beams.

More precisely, our analysis is based on an algorithmic calculation of the possible production and decay modes, considering that the majority of the events proceeds from an on-shell primary production (so that there are no interference effects between the different contributions), with subsequent two-body cascade decays (the exception being 3-body decays of the τ).

For sparticle primary production, we have considered the aforementioned channels[2], i.e. those listed in equations (8) and (9), while for SM primary production we have considered those listed

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[2] Total lepton number violating processes such as $e^+e^- \to \bar\nu\bar\nu$ and $e^-e^- \to \chi_A^-\chi_B^-$ are severely suppressed by the seesaw scale.

in table 2, i.e. W-strahlung for both e^+e^- and e^-e^- collisions, and W- and τ-pair productions for e^+e^- collisions.

In figure 1 we show the results for e^+e^- unpolarised beams for point C_1 (left hand side) and F (right hand side). The cross sections for the signal (red crosses), SUSY background (blue times) and SM background (green asterisks) are given as a function of the centre of mass energy, $\sqrt{s}$. We have taken a degenerate RH neutrino spectrum with $M_R = 10^{12}$ GeV, and $\theta_{13} = 10°$.
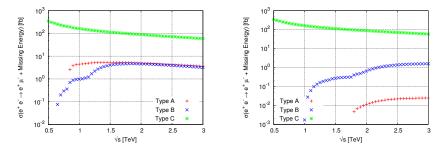

Figure 1. Cross sections for $e^+e^- \rightarrow e^+\mu^- + \not{E}_T$ (with $\not{E}_T = 2\chi_1^0, 2\chi_1^0 + (2,4)\nu, (2,4)\nu$), for points C_1 and F (left and right panels, respectively) as a function of the centre of mass energy $\sqrt{s}$. We fix $M_R = 10^{12}$ GeV, and denote the signal (A) with red crosses, the SUSY charged current background (B) with blue times, and the SM charged current background (C) by green asterisks. We have taken a degenerate right-handed neutrino spectrum and set $\theta_{13} = 10°$.

As can be seen, the SM background, consisting mainly of W-strahlung and W-pair production, dominates the signal by approximately one order of magnitude for C_1 and three orders of magnitude for F. Moreover, the SUSY background dominates (is comparable to) the signal in F (C_1). To understand these two observations, notice that the principal decay modes of sleptons and EW gauginos in F-type points are given by

$$(\tilde{\ell}^-, \tilde{\nu}^*) \rightarrow \chi_2^0(\ell^-, \bar{\nu})\,,\ \chi_1^-(\nu, \ell^+)\,,\ (\ell^-, \bar{\nu})\chi_1^0\,, \tag{11}$$

$$\chi_1^- \rightarrow \tilde{\tau}_1^- \bar{\nu}, W^- \chi_1^0\,, \tag{12}$$

$$\chi_2^0 \rightarrow \tilde{\tau}_1^- \tau^+, Z\chi_1^0\,. \tag{13}$$

while for C-type points we have

$$\chi_1^- \rightarrow \tilde{\ell}^- \bar{\nu}\,,\ \tilde{\nu}^* l^-\,, \tag{14}$$

$$\chi_2^0 \rightarrow \tilde{\ell}^\pm l^\mp\,,\ \tilde{\nu}\bar{\nu}\,,\ \tilde{\nu}^*\nu\,, \tag{15}$$

$$(\tilde{\ell}^-, \tilde{\nu}) \rightarrow (\ell^-, \nu)\chi_1^0\,. \tag{16}$$

Thus, solely from the width of the decays we expect $\Gamma_{\text{total}}(\tilde{\ell})_F > \Gamma_{\text{total}}(\tilde{\ell})_C$, which, for the same amount of flavour violation, gives that the expected signal cross sections for F points should be lower than for C points. In fact, we find that typically $\left(\text{BR}(\tilde{e}_L \rightarrow e\chi_1^0)_C\right)^2 \approx 10 \times \left(\text{BR}(\tilde{e}_L \rightarrow e\chi_1^0)_F\right)^2$.

Additionally, we observe that in C-type points, by taking a centre of mass energy above the $\tilde{\ell}_L\tilde{\ell}_R$ production threshold and below the production threshold of both $\chi_1^+\chi_1^-$ and $\chi_2^0\chi_2^0$, it is possible to evade the largest contribution from SUSY charged current backgrounds. For C_1 this happens above $\sqrt{s} \approx 800$ GeV and below $\sqrt{s} \approx 1200$ GeV, as can be inferred from figure 1.
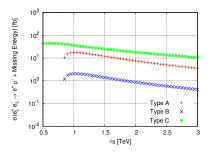
3.1. Beam polarisation effect

Since W-pair production and W-strahlung backgrounds dominate the signal in e^+e^- collisions, it is interesting to consider how beam polarisation can be exploited to suppress their contribution without compromising the signal. We will do this by considering limiting cases, that is, 100% polarisations.

Since slepton flavour mixing occurs predominantly in the LL slepton sector, i.e. via decays of mostly left-handed slepton mass eigenstates, to avoid suppressing the $e^+\mu^-$ signal we require the e^- beam to be 100% left-polarised, while no constraint is placed on the positron beam.

Constraints on the positron beam arise by requiring the suppression of both W-pair production and W-strahlung production cross sections. In W-pair production, the s-channel is strongly dominated by vector boson interactions which can be suppressed by taking equally polarised beams. The t-channel is suppressed either by e_L^+ or e_R^- beams. Therefore, we can suppress both channels by left-polarising the positron beam. Regarding W-strahlung, a maximal suppression would require $e_L^+e_R^-$ which would strongly suppress the signal. Nevertheless, the choice $e_L^+e_L^-$ is preferable to $e_R^+e_L^-$ one.

In figure 2 we show the result of left-polarising both positron and electron beams for point C_1, with parameters and line colour code as in figure 1. Clearly, the signal is enhanced by a factor of ≈ 4 near the $(\tilde{e}_R^+\tilde{e}_L^-)$ production threshold, while at higher energies the enhancement becomes smaller. The low energy tail of the SUSY background "disappears", as is understandable from the fact that such processes proceed via $\tilde{\tau}_1^+\tilde{\tau}_1^-$ primary production. Moreover, both $\chi_1^+\chi_1^-$ and $\chi_2^0\chi_2^0$ primary production are greatly suppressed. As expected, the SM background is also suppressed, becoming comparable to the signal.

Figure 2. Cross section for $e^+e^- \to e^+\mu^- + \not{E}_T$ (with $\not{E}_T = 2\chi_1^0, 2\chi_1^0 + (2,4)\nu, (2,4)\nu$), for point C_1, as a function of the centre of mass energy $\sqrt{s}$, for 100% LL polarised beams. We have taken degenerate right-handed neutrino spectrum with $M_R = 10^{12}$, and set $\theta_{13} = 10°$. Line and colour code as in figure 1.

3.2. Probing the SUSY seesaw

We now discuss how the observation of a signal would allow to probe the underlying mechanism of slepton flavour mixing. If compatible with seesaw predictions, an observation would indeed strengthen the seesaw hypothesis, since a single mechanism would be able to explain many observables: the smallness of neutrino masses while generating neutrino mixings; and collider cLFV. Moreover, low energy observables such as CR(μ-e, N) and BR($\mu \to e\gamma$) would serve to further strengthen the hypothesis, provided that the predictions would be compatible with observations/exclusion limits.

In figure 3 we display the expected number of $e^-\mu^- + 2\chi_1^0$ events from 80% LL polarised electron beams, as a function of the seesaw scale, M_R, for point C_2. For illustrative purposes we have chosen $\sqrt{s} = 2$ TeV.
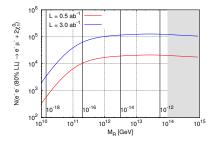

Figure 3. Number of events for $e^-e^- \to e^-\mu^- + 2\chi_1^0$ for point C_2 as a function of the seesaw scale M_R, for $(P_{e^-}, P_{e^-}) = (-80\%, -80\%)$ polarised beams. In both cases, we fix $\sqrt{s} = 2$ TeV, and we have taken a degenerate right-handed neutrino spectrum, with $\theta_{13} = 10°$. Vertical lines denote the M_R-corresponding value of $\mathrm{BR}(\mu \to e\gamma)$ while the (grey) shaded region represents values of M_R already excluded by the present experimental bound on $\mathrm{BR}(\mu \to e\gamma)$.

Due to the high number of expected events, if no $e^-\mu^-$ signal event is observed at an LC, then a high-scale SUSY seesaw is clearly disfavoured. Supposing that events are indeed observed, two possibilities arise. If the observed number of events is not accommodated by predictions, then it is likely that either the SUSY seesaw is not the unique source of LFV or that another mechanism for neutrino mass generation is at work. If the observed number of events can be accommodated by predictions, as illustrated in figure 3 for point C_2, then one can constrain (or even hint at) the seesaw scale. For example, if SUSY is realised with a C_2-like spectrum and more than 10^5 signal events are observed for a total integrated luminosity of approximately 3 ab^{-1}, then the seesaw scale, M_R, should be above 10^{12} GeV. Moreover, evading the exclusion limits on $\mu \to e\gamma$ sets an upper bound on this scale, so that we would be led to 10^{12} GeV $\lesssim M_R \lesssim 10^{14}$ GeV. If we now suppose that $\mu \to e\gamma$ is observed at MEG, e.g. with a branching ratio of the order of 10^{-12}, we would expect a number of $e^-\mu^-$ signal events below 10^5. This incompatibility could be due to (unaccounted for) destructive interferences in collider processes, or additional sources of LFV that only contribute to low-energy observables.

3.3. $\mu^-\mu^-$ golden channel
Same sign di-muon final states may possibly be a "golden channel" for the detection of cLFV at an LC. From an experimental point of view, the efficiency of the muon detectors can be fully explored when looking for di-muon final states. On the theoretical side, higher signal significances are expected, in particular due to very suppressed SM backgrounds.

In figure 4 we display the $e^-e^- \to \mu^-\mu^- + \not{E}_T$ cross section for the signal and the SUSY background, considering unpolarised beams, as a function of the centre of mass energy.

The SM background, not displayed in figure 4, is dominated by double-W-strahlung production, i.e. $e^-e^- \to W^-W^-\nu\nu \to \mu^-\mu^-2(\bar{\nu}\nu)$, whose cross section is of the order of 1 fb. Therefore, we confirm that the $\mu^-\mu^-$ signal event is indeed much cleaner than $e^-\mu^-$ (and $e^+\mu^-$ in e^+e^- collisions).
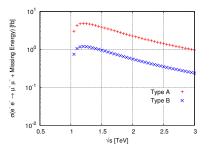
Figure 4. Cross section for $e^-e^- \to \mu^-\mu^- + \not{E}_T$ (with $\not{E}_T = 2\chi_1^0, 2\chi_1^0 + (2,4)\nu$), for point C_1 as a function of the centre of mass energy, $\sqrt{s}$, for the case of unpolarised beams. The signal is denoted by red crosses and the SUSY background by green asterisks. We have taken a degenerate right-handed neutrino spectrum with $M_R = 10^{12}$ GeV and set $\theta_{13} = 10°$.

4. Concluding remarks

A high-energy lepton collider offers an enormous potential for cLFV discovery. Beam polarisation can be instrumental in maximising the signal significance, rendering the signal "visible" in a large part of the high-scale SUSY seesaw parameter space, even without dedicated cuts, which could improve the observation prospects even further. We have also pointed out that cLFV discovery at an LC, complemented with low-energy LFV observables, could substantiate or disfavour the high-scale SUSY seesaw. Finally, we commented on the truly remarkable channel for cLFV discovery: $e^-e^- \to \mu^-\mu^- + 2\chi_1^0$.

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